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Research Article

High-throughput phenotyping of chickpea (*Cicer arietinum* L.) for enhanced tolerance to drought and heat stress

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Abstract

High-throughput phenotyping in the chickpea genotypes, the imaging techniques include in visual (VIS), infrared (IR), and near-infrared range (NIR) for morpho-physiological traits, surface temperature, and plant water relations respectively. To optimize image-based phenotyping methods for assessing plant responses to depleting soil moisture stress and to identify promising traits and potential genotypes for drought tolerance of chickpea genotypes. The chickpea genotype JG-16 was found to be a promising genotype, which can be used as a donor for drought tolerance as it had high biomass relative to Digvijay. The highest digital area pixel, boundary point count, and boundary point roundness during the initial phase in response to two levels in well-watered (C) and water-stressed (S) plants are identified in the JG-16. Responses of chickpea genotypes to soil moisture deficit imposed under field condition conducted with two level of soil moisture stress show the higher biomass accumulation was observed among the D-24, D-15, D-5, D-22 and ICE_10294 under well water conditions while D-22, D-29, and ICE_15654B. Genotypes Such as D-24, D-5, D-15, IPC_06-11, and ICE_15654B had high seed yield and could maintain their canopy cooler in stress conditions induced by soil moisture deficit. Selected ones can be further validated before using them as donors of drought tolerance in chickpea genotypes in breeding programs for drought-prone areas.

Keywords: High-throughput phenotyping, Tolerance, drought, Chickpea, Image analysis

Introduction

Chickpea (*Cicer arietinum* L.) is the third most important legume globally, with its evolutionary origin in the hot, arid regions of Turkey and northern Syria (Toker *et al.,* 2021; Arriagada *et al.,* 2022). It belongs to genus Cicer, tribe Cicereae, family Fabaceae, and subfamily Papilionaceae, and has nine annual and 34 perennial species, has hypogeal germination, a growth habit that can be erect, semi-erect, spreading, semi-spreading or prostrate, with branches emanating from the stem. Chickpea is a highly self-pollinated diploid crop with an outcrossing rate of less than 1%, diploid chromosomes have 2n=16, a genome size of 738.09 Mb and an estimated 28,269 genes (Varshney *et al.,* 2013; Sajja *et al.,* 2017). It is a cool-season leguminous pulse crop cultivated globally, particularly in Afro-Asian regions with abundant nutritional benefits and superior protein quality. However, the escalating impact of global climate change, particularly terminal drought stress, significantly threatens chickpea production, leading to widespread crop yield loss of up to 70% (Pappula-Reddy *et al.,* 2024). However, chickpea genotypes are highly vulnerable to drought and heat stress. Their shallow root systems and limited water-holding capacity make them sensitive to drought, leading to reduced crop productivity and economic losses. Phenotyping techniques play a vital role in identifying and selecting tolerant genotypes, paving the way for the development of climate-resilient chickpea genotypes, and ensuring food security in the face of changing climatic conditions. By developing chickpea varieties with enhanced tolerance to drought stress, we can create more sustainable farming systems that promote environmental stewardship and long-term agricultural viability (Rana *et al.,* 2016; van Oldenborgh *et al.,* 2018). Ultimately, the screening process plays a critical role in adapting chickpea crops to the changing climate, safeguarding food production, and ensuring the resilience of farming communities.

Phenotyping plays a significant role in identifying and selecting tolerant genotypes with enhanced resilience to drought and heat stress. Through phenotyping, researchers can evaluate and quantify the phenotypic variation among different genotypes, allowing for the characterization of traits associated with tolerance (Rane *et al.,* 2021). Traits such as plant height, leaf area, biomass accumulation, root characteristics, physiological parameters, and stress-related biochemical markers can be assessed to determine the performance of genotypes under stress conditions. The efficient screening enabled by phenotyping technologies and methodologies allows for the evaluation of large populations, expediting the identification of tolerant individuals (Basavaraj & Rane, 2020). Furthermore, phenotyping provides valuable insights into the genetic basis and heritability of tolerance traits, aiding in the selection of genotypes with stable and heritable characteristics. The data obtained from phenotyping guide breeding strategies and the development of improved varieties through informed selection, crossbreeding, and targeted genetic transformation.

High-throughput phenotyping (HTP) has emerged as a promising solution, offering fast, precise, and automated data collection methods to expedite the development of drought-adapted cultivars (Kim *et al.,* 2021). High throughput phenotyping of plant germplasm for tolerance

to various abiotic stresses. These facilities allow screening of several hundred plants at a time, and it is possible to screen thousands of lines for responses of plants to a particular phase of crop growth with staggered planting and growth initially under natural conditions. The facility is equipped with cameras for acquiring images in visual (VIS), infrared (IR), and near-infrared range (NIR) for morpho-physiological traits, surface temperature, and plant water relations respectively. Measurement of chlorophyll fluorescence through image-based platforms has provided insights into the photosynthetic efficiency of chickpea plants under water-deficit conditions, helping to identify genotypes with better stress tolerance (Das *et al.,* 2021; Basavaraj *et al.,* 2024; Pappula-Reddy *et al.,* 2024). Automated temperature regulation can allow screening for high-temperature tolerance. Robust software and hardware allow the acquisition, storage, and analysis of huge sets of images. Research projects facilitated by this technology vary from large-scale screening of early growth and tolerance to abiotic factors like soil moisture stress, salinity, and nutrient imbalances (Rane *et al.,* 2021). To identify alternative traits to accelerate the characterization of plants' responses to complex and difficult-to-measure traits associated and identify promising genotypes that have attributes contributing to stress tolerance (Das *et al.,* 2021). To complement the efforts of plant breeders and molecular biologists involved in the investigation of genes associated with tolerance to abiotic stresses in field and horticultural crops. It facilitates the development of low-cost indigenous plant phenotyping tools for controlled and field experiments by validation of results in high throughput (HTP) phenotyping (Basavaraj & Rane, 2020). The wealth of multi-dimensional data generated through HTP can be used to map genotype–phenotype correlations. Further integration of HTP data with QTL data can be useful in breeding programs for precise selection of abiotic–stress–tolerant lines (Pappula-Reddy *et al.,* 2024). This study used digital imaging techniques and manually recorded data to evaluate differences in morpho-physiological traits among the chickpea genotypes in response to drought stress. Its overarching goal was to validate the potential of using automated high-throughput screening methods within a breeding program to enhance drought tolerance in chickpea.

Materials and methods

Plant materials

Experiments conducted with chickpea genotypes obtained from ICAR-India Institute of Pulse Research, Kanpur and Pulses Improvement Project, MPKV, Rahuri. Experiments were conducted at ICAR-NIASM, Baramati, Pune during the period from 2024-2025. List of chickpea genotypes are used in these experiments are as follows (Table 1).

Research methodology

Screening for different chickpea genotypes

Initial experiments at the plant phenomics facility of included soil moisture stress imposed by creating two levels of soil moisture viz., 60-80% of field capacity as control and 40-50% field capacity as stress. However, this method could not create sufficient soil moisture stress for differentiating the genotypes for their tolerance to stress. Hence, it was decided to assess the responses of plants to depleting soil moisture by withholding irrigation at particular growth stages of crop plants. Depletion of soil moisture was recorded almost every day after withholding the irrigation till wilting symptoms appeared in plants. In some experiments, recovery from the soil moisture stress was assessed by replenishing the soil moisture to field capacity and then terminating the experiments after 3 to 5 days (Rascher *et al.,* 2011; Li *et al.,* 2014; Rane *et al.,* 2021).

Table 1: List of chickpea genotypes (control and field condition) in high-throughput phenotyping for drought tolerance

S. No.	Chickpea genotypes				
	Control condition		**Field condition**		
1.	JG-16	ICE-12202	D-9	ICE-15874B	ICE-10243A
2.	BG-3097	ICE-1985	ICE-10294	ICE-16702	ICE-12078
3.	DIBG-505	H-10	D-2	D-27	D-29
4.	RVSS-51	D-28	H-20	D-4	H-29
5.	BG-396	ICE-6565	H-6	H-3	ICE-14886
6.	JG-16-OA	ICE-15872	ICE-4961	ICE-5173	D-7
7.	DIBG-205	ICE-16727	D-14	D-32	D-30
8.	IPC_L19-1	ICE-15860	ICE-15156	D-5	ICE-10254
9.	IPC_L4-14	D-23	D-17	ICE-15660	ICE-15927
10.	RSG-888	D-26	ICE-15020	ICE-15936	ICE-15654B
11.	JAKI-9218	H-8	ICE-9553	D-15	D-22
12.	BG-4005	ICE-16015	ICE-10057	D-18	D-31
13.	NC-1	H-23	ICE-10287	ICE-15874A	
14.	PUSA-362	ICE-10191	D-25	ICE-15654A	
15.	Digvijay	ICE-10941	ICE-15866	ICE-16704	
16.	PUSA-372	H-14	D-13	D-8	
17.	BGM-10218	ICE-10249	ICE-10194	ICE-3468	
18.	JG-11	ICE-3864	ICE-15230	ICE-7550	
19.	DCP-92-3	D-3	ICE-15653	D-12	
20.	ICCV-10	D-16	ICE-10939	IPC06-11	
21.	IPC_L14-16	Digvijay	D-21	H-30	
22.	BGM-10216	ICE-10525	ICE-12048	D-24	

Methods for imposing drought stress

Initial experiments at the plant phenomics facility included soil moisture stress imposed by creating two levels of soil moisture viz., 60-80% of field capacity as control and 40-50% field capacity as stress. However, this method could not create sufficient soil moisture stress for differentiating the genotypes for their tolerance to stress. Hence, it was decided to assess the responses of plants to depleting soil moisture by withholding irrigation at particular growth stages of crop plants. Depletion of soil moisture was recorded almost every day after withholding the irrigation till wilting symptoms appeared in plants. In some experiments, recovery from the soil moisture stress was assessed by replenishing the soil moisture to field capacity and then terminating the experiments after 3 to 5 days (Leinonen & Jones, 2004; Rane *et al.,* 2021; Römer *et al.,* 2012).

Visible imaging

In plant science, visible light imaging has been broadly adopted due to its low cost and simplicity. Using this imaging system, with a similar wavelength (ranging from 400 to 700 nm) perception as the human eye, two-dimensional (2D) images can be used to analyze numerous phenotypic characteristics and to record the changes in plants. To spread the spatial and volumetric information of phenotype images, three-dimensional (3D) imaging approaches have been developed, which could provide more accurate estimations of the morpho-physiological traits. It represents raw data of a phenotype image in spatial matrices based on the intensity values relating to photon fluxes (red~600 nm, green~550 nm, blue~450 nm) of the visible light spectral band (Li *et al.,* 2014; Rane *et al.,* 2021).

Infrared imaging

Infrared imaging technologies are used for screening objects of internal molecular movements which emit infrared radiation. Two popular infrared imaging devices- a near-infrared (NIR) and a far-infrared (Far-IR, also called IR thermal) - can be used to screen radiation images. Many studies have combined visible and NIR imaging to detect vegetative indices because healthy plants reflect a large proportion of NIR light (800-1400 nm), whereas soil reflects little NIR light (Li *et al.,* 2014; Rane *et al.,* 2021).

Fluorescence imaging

Fluorescence imaging is used from laboratory to field. This imaging technique describes the information about the plant metabolic status that can be obtained by the artificial excitation of the plant photo systems and observation of the relevant responses (Li *et al.,* 2014). It is based on charge-couple device (CCD) cameras with sensitive fluorescence signals, where the signals occur by illuminating samples with visible or ultraviolet light. There are two types of fluorescence (red to the far-red region and the blue to green region) generated by the ultraviolet illumination ranging from 340 to 360 nm and is expressed as a principle of underlying multi colour fluorescence imaging. This technique offers the simultaneous capture of fluorescence emission and provides a quick way to probe photosystem II status in vivo (Maxwell & Johnson, 2000).

Image analysis

Once the images are captured, image analysis techniques are utilized to extract quantitative information from the images (Li *et al.,* 2014; Rane *et al.,* 2021). This involves processing the images using software or algorithms to measure parameters such as leaf coverage, density, or biomass. Image analysis helps in obtaining objective and consistent data for further analysis.

Data analysis

After collecting the relevant data, statistical methods and data analysis techniques are applied to analyse and interpret the findings (Li *et al.,* 2014; Rane *et al.,* 2021). This step involves performing calculations, statistical tests, and modelling to determine the impact of stress on genotype performance, identify patterns, and draw meaningful conclusions.

Data interpretation

Data interpretation involves making sense of the analyzed results and drawing conclusions based on the findings (Rane *et al.,* 2021; Li *et al.,* 2014). Interpretation often involves comparing the experimental results with existing literature, discussing limitations, and suggesting future research directions

Results and discussion

The present investigation on the 'high-throughput phenotyping of chickpea for enhanced tolerance to drought and heat stress'. Experiment was conducted on high-throughput phenotyping of chickpea for enhanced tolerance to drought and heat by using control condition phenotyping as well as field condition. The stress imposition refers to intentionally subjecting the genotypes to specific environmental conditions to evaluate their performance. The forward genetics approach is all about understanding the trait inheritance using the phenotypic data and, in most cases, it is the mutant phenotypes that formed the basis for understanding of gene functions.

High-throughput phenotyping (Control condition)

An experiment was conducted to optimize image-based phenotyping methods for assessing plant responses to depleting soil moisture stress and to identify promising traits and potential genotype (s) for drought tolerance with 22 genotypes of chickpea including local check Digvijay (Figure 1). Optimization of high-throughput phenotyping protocol for heat tolerance in chickpea have evaluated the plants initially grown under natural conditions in pots were shifted to a plant phenomics facility 30 days after sowing (DAS) for phenotyping. Heat stress treatment was imposed

at 30 DAS by shifting one set of genotypes to a heat chamber where an average 35°C temperature was maintained and the other set was kept in normal condition maintained as control. High-resolution visible (400-700 nm), NIR (700-1700 nm), and IR camera sensors were used to capture images of shoot image parameters in different pots (Rane *et al.,* 2021; Chaudhry & Sidhu, 2022).

Soil moisture (SM) trends and near-infrared (NIR) intensity show a strong, typically inverse, relationship in both control and drought stress treatments. As soil dries due to drought stress, NIR reflectance generally increases, while in well-watered (control) scenarios with high soil moisture, the NIR reflectance decreases due to increased water absorption (Figure 2). High-resolution visible (400-700 nm) and NIR (700-1700 nm) sensors were used to capture images of shoot image parameters in different pots. Based on high-throughput phenotyping studies in chickpea genotypes, heat map analyses of image-based parameters are used to differentiate water-stressed from well-watered plants, with significant colour variations reflecting stress-induced reductions in plant structure and canopy temperature changes (Bita & Gerats, 2013). Parameters include increased leaf surface temperature, lower chlorophyll reflectance, significant morphological changes (wilting, reduced leaf area), and higher spectral water stress indices (Figure 3). Drought stress causes a significant reduction in the mean values of digital area (a), convex hull area (b), and boundary point count (c) of shoots, reflecting decreased biomass production, reduced shoot expansion, and thinner plant structure. Drought-tolerant genotypes exhibit less

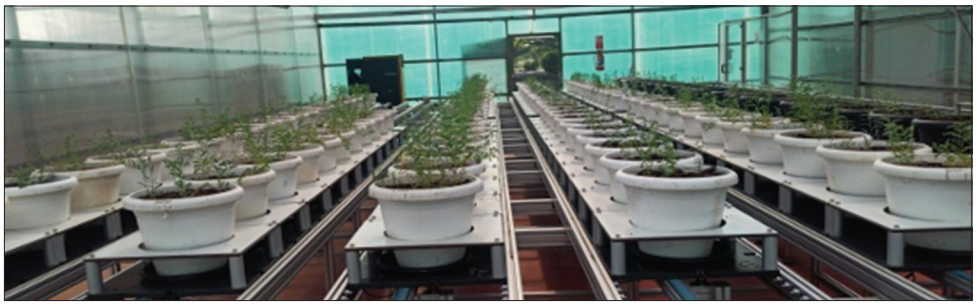


Figure 1: Experimental setup in plant phenotyping facility

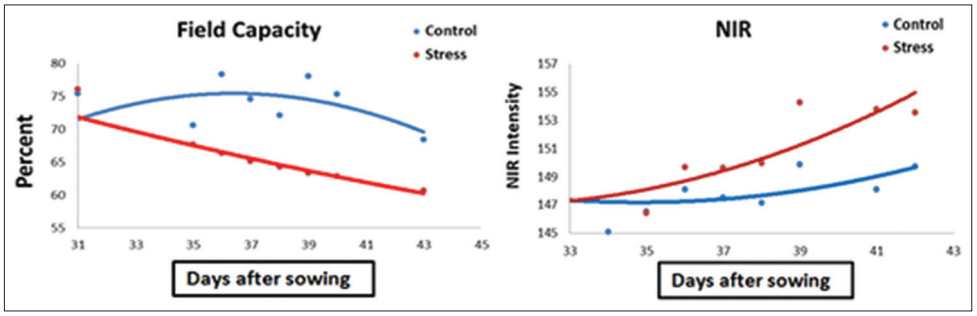


Figure 2: Soil moisture trends and NIR intensity in control and drought stress treatment

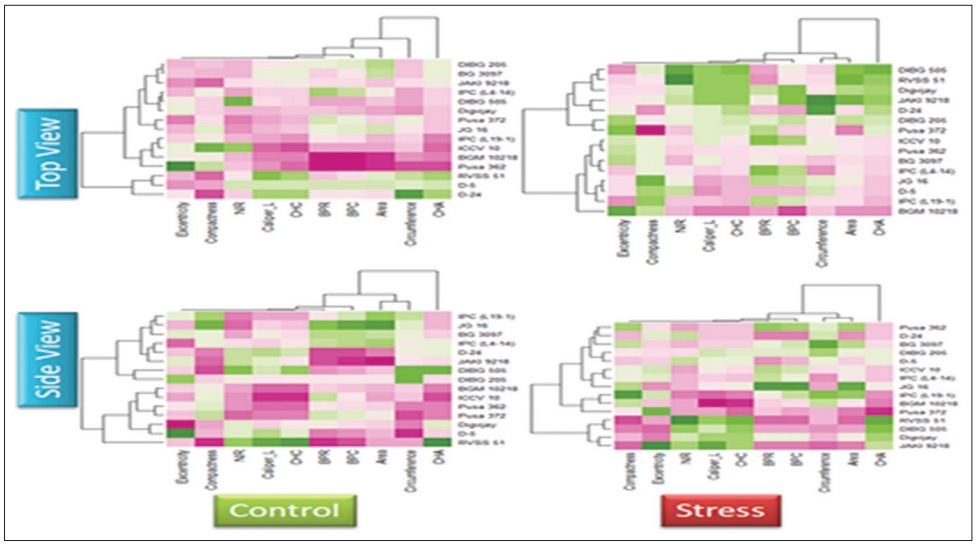


Figure 3: Heat Map: Image parameters differentiating plant responses to water stress and well-watered condition from top and side view

of a decline in these digital traits compared to sensitive genotypes, maintaining higher projected areas and better growth under water stress (Figure 4). Image parameters significantly differentiate plant responses to heat stress on top and side views ratio of digital area pixel (a) ratio of convex hull rea (a) and ratio of boundary point count (a). Parameters such as digital area, convex hull area (CHA), boundary point count (BPC), as well as NIR intensity, could differentiate the responses of chickpea genotypes more efficiently under depleting soil moisture (Figures 5-7). Chickpea genotypes evaluated in high-throughput studies for the water stress condition often exhibiting a lower boundary point count compared to well-watered counterparts, reflecting reduced leaf area and biomass accumulation (Chaudhry & Sidhu, 2022). Parameters such as digital area, convex hull area (CHA), and boundary point count (BPC) could differentiate the responses of chickpea genotypes more efficiently under depleting soil moisture. Chickpea genotype JG-16 showed the highest digital area pixel, boundary point count, and boundary point roundness during the initial phase in response to two levels in well-watered (C) and water-stressed (S) plants (Rascher *et al.,* 2011; Li *et al.,* 2014; Rane *et al.,* 2021).

The genetic variation is crucial for identifying drought-tolerant genotypes, as some lines maintain higher boundary point counts despite water deficits

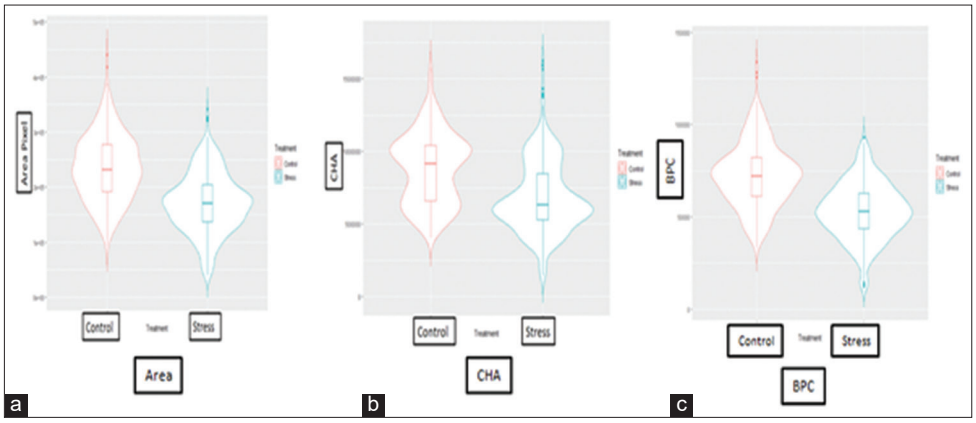


Figure 4: Mean values of digital area a) Convex hull area, b) Boundary Point Count and c) of shoots of chickpea plants in drought and control conditions

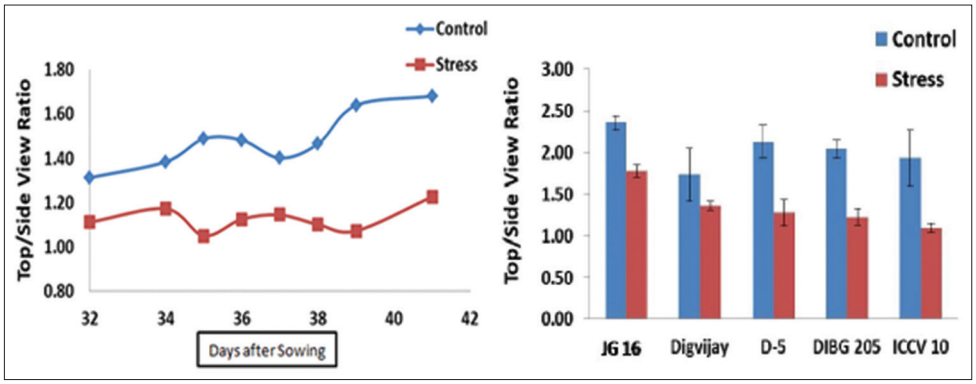


Figure 5: Top and side view ratio of digital area pixel. Genotypic variation under control and drought condition (40 DAS)

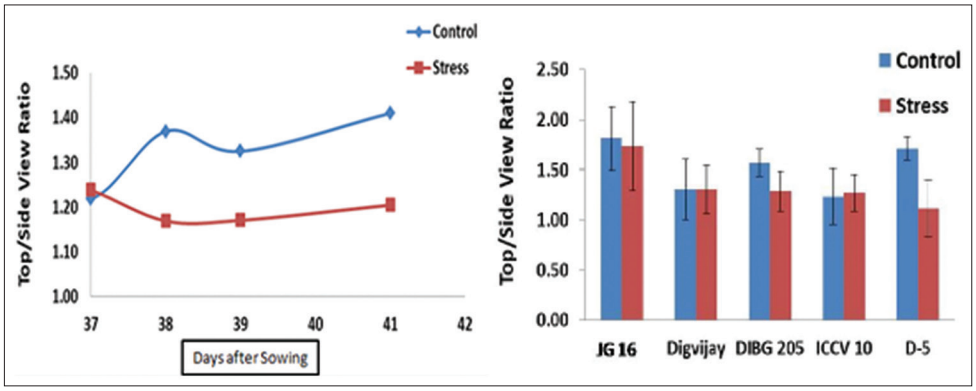


Figure 6: Top and side view ratio of convex hull area. Genotypic variation under control and drought conditions (40 DAS)

(Figure 8). Genetic variation in boundary point counts a phenomic trait derived from image analysis to measure leaf complexity and shape shows significant differences between chickpea genotypes and in response to water availability during early development. Boundary point count, in combination with leaf area and compactness, differentiates lines between control and stressed conditions (Chaudhry & Sidhu, 2022). It helps characterize leaf area and architecture under well-watered (C) and water-stressed (S) conditions (Figure 9). Digital area, representing the total canopy size or projected leaf area in chickpea genotypes, is a critical phenotyping trait used in high-throughput studies to quantify biomass and growth responses to heat stress. Under heat stress, chickpea genotypes generally experience a significant reduction in digital area (linked to lower biomass and leaf area index), with substantial differences observed in how genotypes maintain this area under high-temperature conditions (Figure 10). Chickpea genotype JG-16 was found to be a promising genotype, which can be used as a donor for drought tolerance as it had high biomass relative to Digvijay. To optimize image-based phenotyping

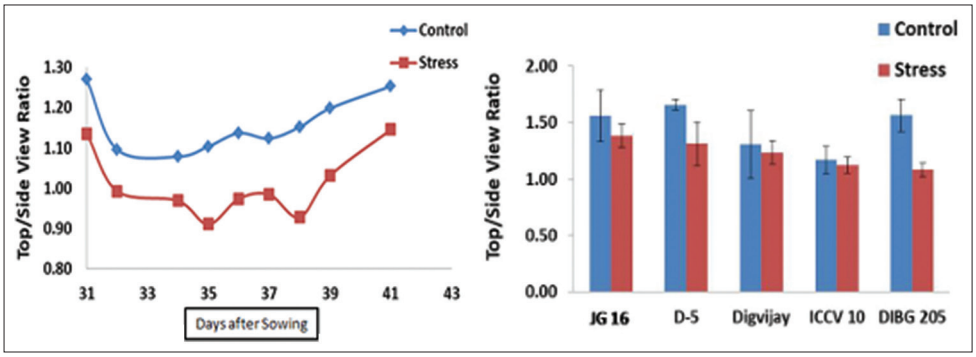


Figure 7: Top and side view ratio of boundary point count. Genotypic variation under control and drought condition (40 DAS)

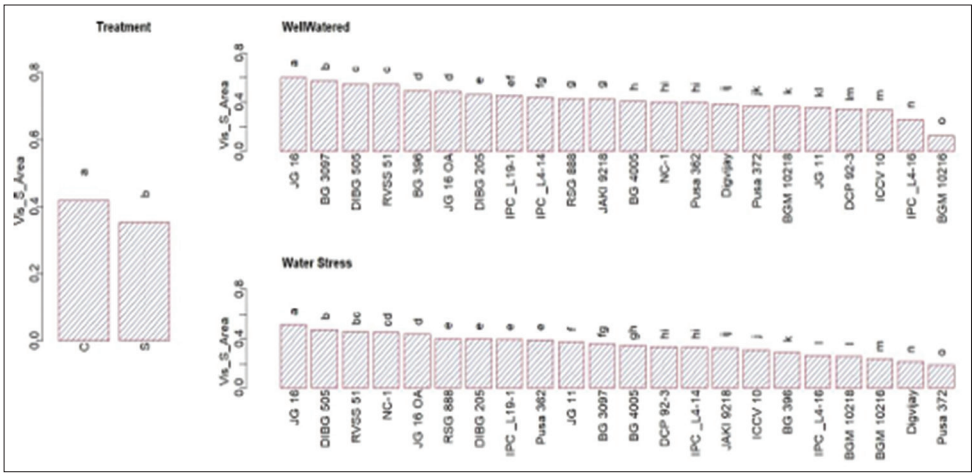


Figure 8: Genetic variation in digital area pixel during the initial phase in response to two levels in well-watered (C) and water-stressed (S) plants

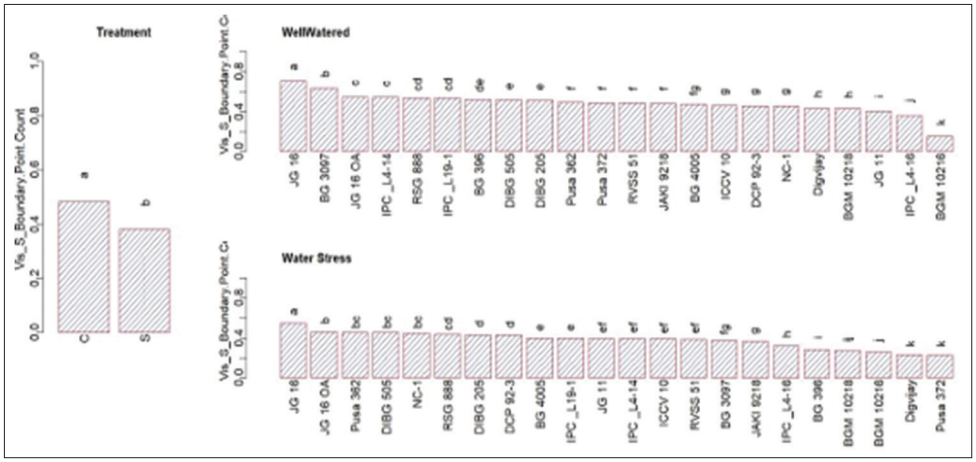


Figure 9: Genetic variation in boundary point count during the initial phase in response to two levels in well-watered (C) and water-stressed (S) plants

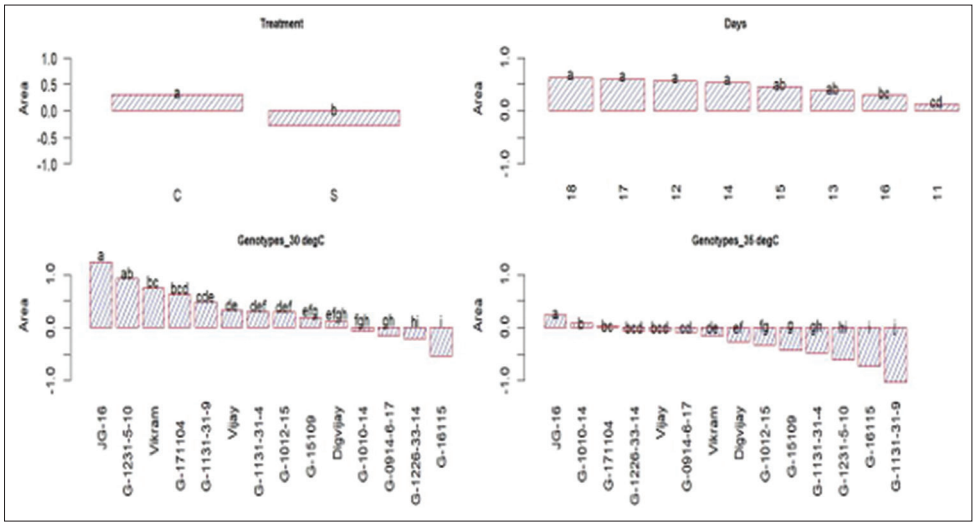


Figure 10: Treatment, day-wise, and genotypic differences in digital area in chickpea genotype under control and heat stress

methods for assessing plant responses to depleting soil moisture stress and to identify promising traits and potential genotypes for drought tolerance of chickpea genotypes (Das *et al.,* 2021; Chaudhry & Sidhu, 2022; Basavaraj *et al.,* 2024).

High-throughput phenotyping (Field condition)

This experiment was conducted with two level of soil moisture stress created by varying number of irrigations. The well-watered plants had two irrigations while stressed plots had only one irrigation. Each of the treatment had three replications and each replication had 78 genotypes including a local check named Digvijay. Sowing was carried out on 15th Nov 2024. The irrigated treatment received the last irrigation on 30th Dec 2024 while the stressed plots did not receive any irrigation till the harvest. There were no rains during the experiments. Experiment was conducted with Randomized Block design and with 1.8 m ×1.5 m plots (Figure 11). Crop was provided with 20-60-00 Kg/ha of N-P-K as basal doze. Most of the time the soil up to 30 cm was dry with only about 8% moisture in stressed plots and about 10-18% moisture in irrigated plots.

Responses of chickpea genotypes to soil moisture deficit imposed under field condition concluded that the early flowered genotypes D-13, D-15, D-30 & D-31 maintained cooler canopy & high Vegetative index than Digvijay, the local check. Chickpea genotypes ICE_15654A, ICE_15654B, IPC_06-11 & ICE_15660 revealed a high Vegetative index as well as maintained their canopy cooler than Digvijay. Genotypes Such as D-24, D-5, D-15, IPC_06-11, and ICE_15654B had high seed yield and could maintain their canopy cooler in stress conditions induced by soil moisture deficit. Higher biomass accumulation was observed among D-24, D-15, D-5, D-22 and ICE_10294 under well water conditions while D-22, D-29, and ICE_15654B under water stress conditions Substantial genetic variation exists among



Figure 11: Chickpea genotypes to soil moisture deficit imposed under field condition

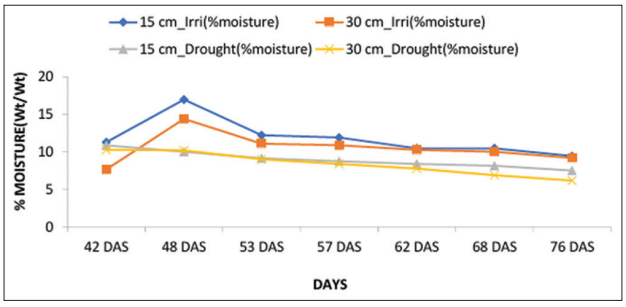


Figure 12: a) View of field experiments conducted with 78 genotypes and b) the soil moisture levels at 15 and 30 cm during the experiments

chickpea genotypes for canopy temperature depression (CTD), biomass accumulation, and seed yield, indicating strong potential for selecting heat- and drought-tolerant lines (Figure 13). High temperature and drought stress severely reduce biomass and seed yield, primarily by shortening the growth period and causing flower/pod abortion. While heat stress reduces plant height and biomass, the most impacted trait is the number of pods per plant, which directly lowers the seed yield (Das *et al.,* 2021; Rane *et al.,* 2021; Basavaraj *et al.,* 2024). The study suggests that for better yield, especially in rainfed conditions, it is crucial to select genotypes that have better root development to tap moisture from the 15-30 cm depth, which is the most active zone of moisture extraction (Figure 12).

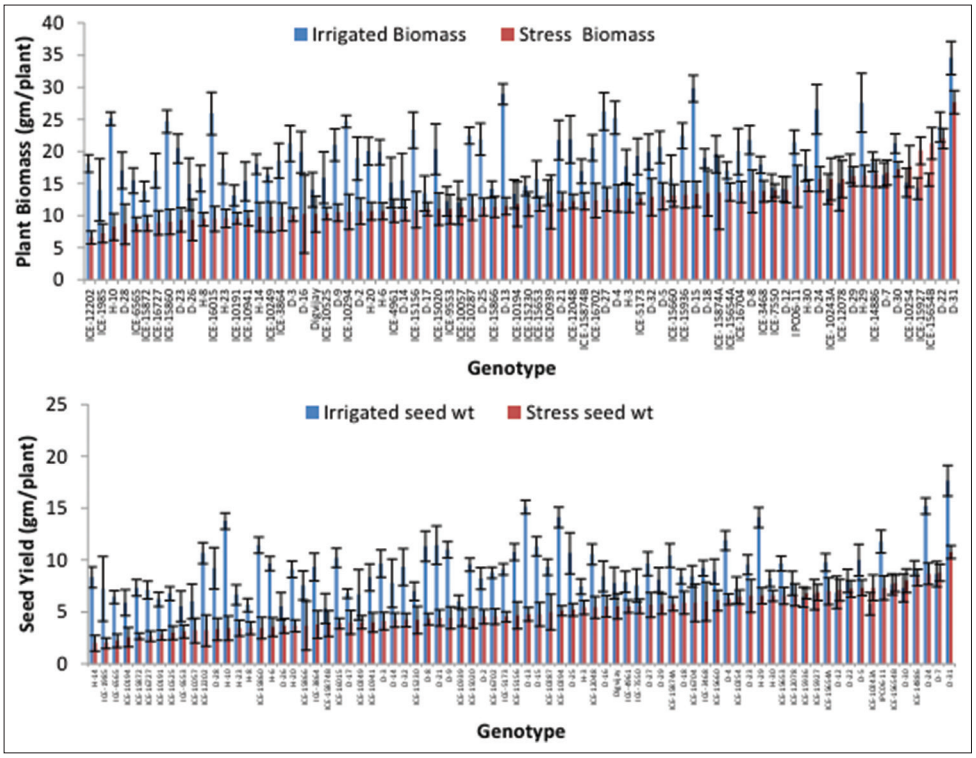


Figure 13: a) Variation in canopy temperature, b) biomass and c) seed yield per plant in chickpea genotypes tested under field conditions

Conclusions

Experiment was conducted on high-throughput phenotyping of chickpea for enhanced tolerance to drought by using control condition phenotyping as well as field condition phenotyping. Optimization of high-throughput phenotyping protocol for heat tolerance in chickpea have evaluated the plants initially grown under natural conditions in pots were shifted to a plant phenomics facility 30 days after sowing (DAS) for phenotyping. Parameters such as digital area, convex hull area (CHA), boundary point count (BPC), as well as NIR intensity, could differentiate the responses of chickpea genotypes more efficiently under depleting soil moisture. Chickpea genotype JG-16 showed the highest digital area pixel, boundary point count, and boundary point roundness during the initial phase in response to two levels in well-watered (C) and water-stressed (S) plants. The predicted biomass was used to compute the plant growth rates and water-use indices, which were found to be highly promising surrogate traits as they could differentiate the response of genotypes to soil moisture stress more effectively. Chickpea genotype JG-16 was found to be a promising genotype, which can be used as a donor for drought tolerance as it had high biomass relative to Digvijay. To optimize image-based phenotyping methods for assessing plant responses to depleting soil moisture stress and to identify promising traits and potential genotypes for drought tolerance of chickpea genotypes.

Responses of chickpea genotypes to soil moisture deficit imposed under field condition conducted with two level of soil moisture stress created by varying number of irrigations. The well-watered plants had two irrigations while stressed plots had only one irrigation. The early flowered genotypes D-13, D-15, D-30 & D-31 maintained cooler canopy & high vegetative index than Digvijay, the local check. Genotypes ICE_15654A, ICE_15654B, IPC_06-11 & ICE_15660 revealed a high Vegetative index as well as maintained their canopy cooler than Digvijay. Genotypes Such as D-24, D-5, D-15, IPC_06-11, and ICE_15654B had high seed yield and could maintain their canopy cooler in stress conditions induced by soil moisture deficit. Higher biomass accumulation was observed among D-24, D-15, D-5, D-22 and ICE_10294 under well water conditions while D-22, D-29, and ICE_15654B under water stress conditions. The chickpea phenotyping protocol may be useful in predicting the field performance of breeding lines. This study can help in screening of chickpea genotypes non-invasively to identify potential genotypes of chickpea that can perform better under drought conditions rapidly. The study suggests that for better yield, especially in rainfed conditions, it is crucial to select genotypes that have better root development to tap moisture from the 15-30 cm depth, which is the most active zone of moisture extraction. Selected ones can be further validated before using them as donors of drought tolerance in chickpea cultivars in breeding programs for drought-prone areas.

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Author contributions

Author contributed to the study conception, design, materials and methodology preparation, collection and analysis data were performed. Authors read and approved of the final manuscript.

References

Arriagada, O., Cacciuttolo, F., Cabeza, R. A., Carrasco, B., & Schwember A. R. (2022). A comprehensive review on chickpea (*Cicer arietinum* L.) breeding for abiotic stress tolerance and climate change resilience. *International Journal of Molecular Sciences, 23*(12), 6794. https://doi.org/10.3390/ijms23126794

Basavaraj, P. S., & Rane, J. (2020). Avenues to realize potential of phenomics to accelerate crop breeding for heat tolerance. *Plant Physiology Reports, 25*, 594-610. https://doi.org/10.1007/s40502-020-00552-2

Basavaraj, P. S., Jangid, K. K., Babar, R., Rane, J., Boraiah, K. M., Harisha, C. B., Halli, H. M., Pradhan, A., & Reddy, K. S. (2024). Genetic variation in deficit moisture stress tolerance of *Cicer* accessions revealed by chlorophyll fluorescence. *Genetic Resources and Crop Evolution, 71*, 4723-4737. https://doi.org/10.1007/s10722-024-01937-0

Bita, C. E., & Gerats, T. (2013). Plant tolerance to high temperature in a changing environment: Scientific fundamentals and production of heat stress-tolerant crops. *Frontiers in Plant Science, 4*, 273. https://doi.org/10.3389/fpls.2013.00273

Chaudhry, S., & Sidhu, G. P. S. (2022). Climate change regulated abiotic stress mechanisms in plants: A comprehensive review. *Plant Cell Reports, 41*, 1-31. https://doi.org/10.1007/s00299-021-02759-5

Das, A., Basu, P. S., Kumar, M., Ansari, J., Shukla, A., Thakur, S., Singh, P., Datta, S., Chaturvedi, S. K., Sheshshayee, M. S., Bansal, K. C., & Singh, N. P. (2021). Transgenic chickpea (*Cicer arietinum* L.) harbouring AtDREB1a are physiologically better adapted to water deficit. *BMC Plant Biology, 21*, 39. https://doi.org/10.1186/s12870-020-02815-4

Kim, J., Kim, K.-S., Kim, Y., & Chung, Y. S. (2021). A short review: comparisons of high-throughput phenotyping methods for detecting drought tolerance. *Scientia Agricola, 78*(4), e2019030030. https://doi.org/10.1590/1678-992X-2019-0300

Leinonen, I., & Jones, H. G. (2004). Combining thermal and visible imagery for estimating canopy temperature and identifying plant stress. *Journal of Experimental Botany, 55*(401), 1423-1431. https://doi.org/10.1093/jxb/erh146

Li, L., Zhang, Q., & Huang, D. (2014). A review of imaging techniques for plant phenotyping. *Sensors, 14*(11), 20078-20111. https://doi.org/10.3390/s141120078

Maxwell, K., & Johnson, G. N. (2000). Chlorophyll fluorescence-A practical guide. *Journal of Experimental Botany, 51*(345), 659-668. https://doi.org/10.1093/jexbot/51.345.659

Rana, D. S., Dass, A., Rajanna, G. A., & Kaur, R. (2016). Biotic and abiotic stress management in pulses. *Indian Journal of Agronomy, 61*, S238-S248.

Rane, J., Singh, A. K., Kumar, M., Boraiah, K. M., Meena, K. K., Pradhan, A., & Prasad, P. V. V. (2021). The adaptation and tolerance of major cereals and legumes to important abiotic stresses. *International Journal of Molecular Sciences, 22*(23), 12970. https://doi.org/10.3390/ijms222312970

Rascher, U., Blossfeld, S., Fiorani, F., Jahnke, S., Jansen, M., Kuhn, A. J., Matsubara, S., Märtin, L. L. A., Merchant, A., Metzner, R., Müller-Linow, M., Nagel, K. A., Pieruschka, R., Pinto, F., Schreiber, C. M., Temperton, V. M., Thorpe, M. R., van Dusschoten, D., van Volkenburgh, E.,… Schurr, U. (2011). Non-invasive approaches for phenotyping of enhanced performance traits in bean. *Functional Plant Biology, 38*(12), 968-983. https://doi.org/10.1071/FP11164

Römer, C., Wahabzada, M., Ballvora, A., Pinto, F., Rossini, M., Panigada, C., Behmann, J., Léon, J., Thurau, C., Bauckhage, C., Kersting, K., Rascher, U., & Plümer, L. (2012). Early drought stress detection in cereals: Simplex volume maximisation for hyperspectral image analysis. *Functional Plant Biology, 39*(11), 878-890. https://doi.org/10.1071/FP12060

Sajja, S. B., Samineni, S., & Gaur, P. M. (2017). Botany of Chickpea. In R. K. Varshney, M. Thudi & F. Muehlbauer (Eds.), *The Chickpea Genome* (pp. 13-24). Springer.

Sneha-Priya, P.-R., Kumar, S., Pang, J., Chellapilla, B., Pal, M., Miller, A. H., & Siddique, K. H. M. (2024). High-throughput phenotyping for terminal drought stress in chickpea (*Cicer arietinum* L.). *Plant Stress, 11*, 100386. https://doi.org/10.1016/j.stress.2024.100386

Toker, C., Berger, J., Eker, T., Sari, D., Sari, H., Gokturk, R. S., Kahraman, A., Aydin, B., & von Wettberg, E. J. (2021). *Cicer turcicum*: A new *Cicer* species and its potential to improve chickpea. *Frontiers in Plant Science, 12*, 662891. https://doi.org/10.3389/fpls.2021.662891

van Oldenborgh, G. J., Philip, S., Kew, S., van Weele, M., Uhe, P., Otto, F., Singh, R., Pai, I., Cullen, H., & AchutaRao, K. (2018). Extreme heat in India and anthropogenic climate change. *Natural Hazards and Earth System Sciences, 18*(1), 365-381. https://doi.org/10.5194/nhess-18-365-2018

Varshney, R. K., Song, C., Saxena, R. K., Azam, S., Yu, S., Sharpe, A. G., Cannon, S., Baek, J., Rosen, B. D., Tar'an, B., Millan, T., Zhang, X., Ramsay, L. D., Iwata, A., Wang, Y., Nelson, W., Farmer, A. D., Gaur, P. M., Soderlund, C., Cook, D. R. (2013). Draft genome sequence of chickpea (*Cicer arietinum*) provides a resource for trait improvement. *Nature Biotechnology, 31*, 240-246. https://doi.org/10.1038/nbt.2491